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Procedia CIRP 60 (2017) 62 – 67

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27th CIRP Design 2017

An Investigation into the Interrelationship between Aircraft Systems and Final Assembly Process Design

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Abstract

Modern aircraft are more integrated with advanced systems functionalities, which result in ever-increasing aircraft complexity, further development difficulties and development delays. These system complexities are mostly in the form of system interactions that make it difficult to understand the overall system characteristics. At the early stages of final assembly line (FAL) design, one of the most important objectives is to arrange the installation and test tasks from components to sub-systems and systems in the proper sequence to meet the designed functions and prevent hazards from the integration process. Improper sequencing of the final assembly process will cause rework, time delays, cost and potential safety risk in development. In the field of final assembly line design, previous research has mostly focused on assembly line balancing or supply chain design based on structural parts assembly. However, these approaches do not consider the early final assembly line definition or test allocation for system functions. In this paper, the research proposes a method based on a systems engineering view and integrated computer aided design (CAD) to help better understand system interactions and generate viable final assembly process sequencing. This research aims to develop a concept of unified master data for final assembly design, which contains 3D geometrical CAD, system functions and interaction characteristics. The paper will present the methodology framework, key concepts and associated industrial software packages for implementation. The paper concludes with further discussion of an initial case study.

Peer-review under responsibility of the scientific committee of the 27th CIRP Design Conference

Keywords: Aircraft Systems Integration, Final Assembly Process Design, Integrated CAD

1. Introduction

Aviation industries are making great efforts all the time to develop more comfortable, efficient, reliable, intelligent and low cost aircraft. The development of aircraft systems makes a significant contribution to many of the high-level requirements which are related to advanced functions. As aircraft systems are a typical example of complex system[1,2], the highly integrated system architecture and interactions raise product complexities and cause issues in both design and manufacturing. Thus, systems engineering (SE) is introduced to deal with these complexities and issues. However, Systems Engineering principles and guidelines, for example SAE ARP4754A Guidelines for Development of Civil Aircraft and Systems[3], are mostly covered and applied to systems integration in aircraft system design but not at the manufacturing stage.

In the aircraft system development process, final assembly is recognised as a particular and important development stage. It is the time that individual components are assembled together to build the product from sub-systems, systems to complete aircraft. Therefore, the design and industrialization of modern advanced aircraft is a complex system integration process. There are two main concerns involved in this integration process: firstly, bringing aircraft system design requirements and specifications into the roll-out aircraft through assembly process; secondly, bringing manufacturing strategies, tooling, process capacity and related resources together to balance the cost, time and quality in the form of documented assembly plans. In this field, many previous researchers concentrate on the latter one, assuming that there is a designed final assembly process ready to be used[4]. Some researches try to use knowledge-based solutions embedded into 3D CAD system to improve the process of

Peer-review under responsibility of the scientific committee of the 27th CIRP Design Conference
doi:10.1016/j.procir.2017.01.056

early final assembly line design [5,6]. In addition, the design for manufacture and assembly (DFMA) principle is widely used in assembly system design. Some researchers combine DFMA with digital modelling and simulation to generate assembly sequencing and validate assembly line alternatives[7]. In these researches, the initial FAL process and station allocation are determined mostly by major structural sections join-up processes[8] or directly following the product breakdown structure (PBS)[9]. The relationship between structures and systems, and their relationship to different integration activities in FAL are not fully recognized. Although the importance of FAL design at an early stage is acknowledged, and most previous research applies digital design technologies to improve FAL design quality, they seldom comment on final assembly process design issues from the perspective of system complexities, which are the basis for later development. A method is required to help FAL engineers better understand aircraft system complexities and generate a feasible FAL process at an early stage in the design process.

This paper is structured as follows: Section 2 explains the integrated nature of aircraft final assembly. Then section 3 proposes a design framework based on integrated CAD system, followed by the benefits and challenges in section 4. Section 5 makes conclusions and states future work in brief.

2. Aircraft Systems Integration at Final Assembly Stage

This section describes the complexities of aircraft systems, and how systems are integrated through FAL process, which is the basis for the development of proposed method.

2.1. Aircraft final assembly

The scope of final assembly varies from company to company and from one aircraft to another. This is mainly due to different marketing strategies, manufacturing capacities and aircraft technological specifications. Examples can be found on modern civil and military projects where major section assemblies arrive at FAL with some systems installed by subcontractors or provider[10]. But generally, the main activities and tasks in final assembly can be concluded as: joining major structure sections, installing systems which are not suitable for earlier stage and testing the developing and complete aircraft[11,12]. To limit the scope, this paper assumes that most of system components that can be accessed after structure joining are integrated in final assembly stage. In the FAL design process, tasks are designed and allocated to assembly stations in the early FAL design stage.

Figure 1 shows two main FAL layouts implemented in industry, which are bench layout and flow line [13]. Sometimes bench layout is also known as fixed-position or slant assembly[14], while the flow line layout consists of pulsed-line and continuous moving line. Since the flow line layout is easier for waste reduction and mass production, it is widely used in FAL today.

The layout in Figure 1(b) is a typical pulsed-line organized by stations and normally named with countdown numbers. As each station has an equal takt time, a continuous moving line can be treated as a pulsed-line that includes many stations of short takt time.

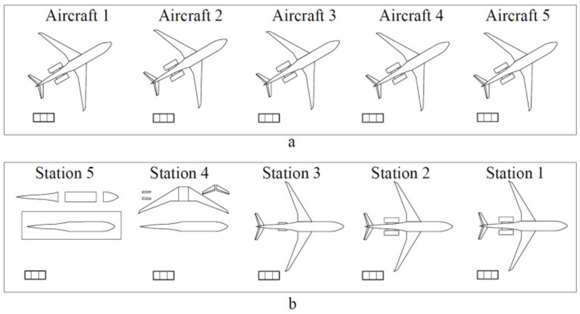

Fig. 1. (a) Bench layout (b) Flow line layout

In final assembly design process, the assembly layout and FAL task allocation are designed in the early development stage, which are concurrent with the product design process in current engineering. If the aircraft itself is treated as a top level complex system, aircraft structure can be considered as one of the sub-system which is the basis for later systems integration. Thus, the main activities of FAL task allocation are to decide the interface between stations. The previous approach that uses structure join-up processes to determine stations is not suitable for a continuous moving line with many stations, because structure join-ups are only a small part of the overall process. A profound understanding of aircraft functions and systems is of importance for FAL design. However, this heavily depends on personal experience because the FAL engineer must fully understand system complexities, and combine systems functions and interactions with assembly processes to determine the best integration sequence for the system components.

2.2. Characteristics of aircraft system integration

An aircraft is a system of systems that can be represented in a hierarchy. In most commercial and military aircraft, the top level sub-systems are defined as structure, vehicle systems, avionic systems and mission systems. Two types of integration characteristics, physical and information based, are found in these sub-systems[15]. Table 1 shows a comparison of integration characteristics for these sub-systems of modern advanced aircraft.

Table 1. Characteristics of integration in modern advanced aircraft[15]

System	Physical integration	Information based integration
Structure	Strong	N/A
Vehicle systems	Strong	Medium to strong
Avionic systems	Weak	Strong
Mission systems	Weak	Strong

It is noticed that vehicle systems show both strong physical and information based integration. This is because vehicle systems like fuel system and propulsion system have strong physical interactions with the structure. Furthermore, information based interactions are found on vehicle systems with the federated controlled and integrated modular controlled architectures on many new aircraft.

The lower level sub-systems of sub-systems are also complex systems themselves, which makes the complexities even harder to understand. In order to illustrate the problem, the interactions of structure, vehicle systems and avionic systems and their sub-systems can be represented in design structure matrix (DSM) and transformed to a dependency network as shown in Figure 2 for a representative set of high level aircraft systems. Dealing with these complexities is a major task in aircraft development and makes the choice of design and manufacturing philosophy of crucial importance.

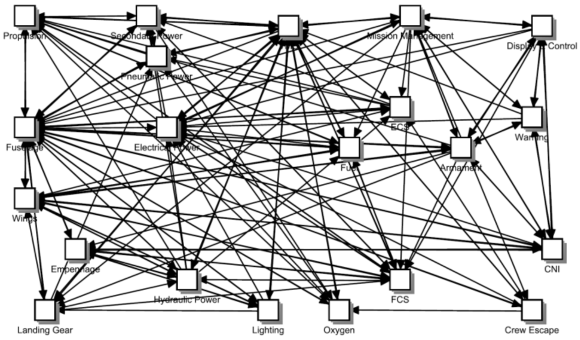

Fig. 2. Example of sub-systems interactions complexities

2.3. Relationship of installation and test processes in FAL

Integration objectives at the final assembly stage consist of structure sections, hardwired cable harnesses, data buses, pipes, support brackets and equipment from different sub-systems. As stated by Fritz et al for complex system the function is "almost entirely emergent, i.e., not directly related to any physical property of the implementation" [16]. The highly interactive and coupled systems indicate that if one sub-system fails to meet designed specifications then other sub-systems, systems and even the entire aircraft may not perform correctly. This means the FAL integration process must be designed towards system functions and interactions. In final assembly, physical integration is in the form of installation which is the basis for further installation and test. By contrast, the information based integration method in FAL refers mostly to test including wiring correctness test, mechanical test, power on test and factory functional test (FFT). This process is in accordance with the dramatic increasing system installations. Test is also an effective method to verify assembly quality and designed specifications in FAL.

The highly integrated system architecture employed by modern advanced aircraft requires strict integration sequencing in FAL. Compared with distributed system architecture, federated controlled architecture and integrated modular controlled architecture are more integrated. Their sub-system control logic is integrated in a central computer rather than components and equipment in sub-system. The components of sub-systems are connected with vehicle interface units (VIU), and VIUs transform control single through high speed data buses[1]. Thus, FAL process design should follow the principle that: firstly, to ensure the as planned integration meets sub and whole system design specifications by system hierarchy; secondly, to ensure that the as manufactured systems still meet design specifications in FAL operating environment. Then, the generic relationship of installation and different tests can be drawn in Figure 3.

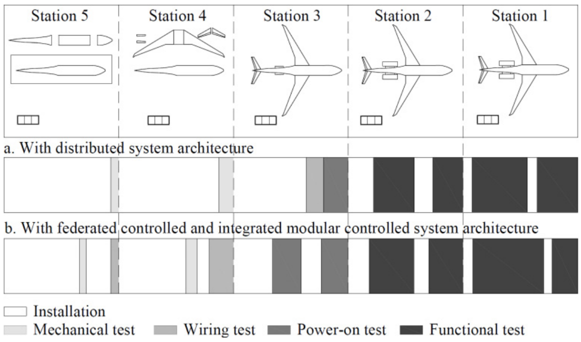

Fig. 3. Example of installation and test processes relationship with different system architectures

Figure 3 shows that with integrated system architecture, more tests are found in the whole FAL process, and electric related tests are arranged earlier than distributed system architecture. This FAL process has the advantage of fulfilling system verification requirements and ensuring the integration quality. However, issues can also be caused if following this principle:

- Low tolerance for design and manufacture error
- Less flexibility for FAL tasks allocation
- Difficulty of arranging tests in one fixed station

In addition, aircraft design data is delivered to manufacturing in the form of drawings or 3D CAD by individual systems after detailed design. The data organized in PBS of one system only includes the geometric information that need for installation operations design. What is more, the requirements of test are documented separately for one system too. This leads to the difficulty of understand systems interactions and FAL process design constraints from other systems. Hence, current design data do not indicate at what installation stage should arrange a test to verify designed specifications for FAL.

3. Integrated CAD Approach Framework and Implementation Architecture

Aircraft final assembly design is now undertaken concurrently with product design. The DFMA principle suggests that assembly planning must be taken into account as early as possible in the product design cycle[17]. In early FAL design stage, one of the issues is how to access available design information to generate the initial FAL solutions and alternatives. Apart from geometrical data, generic product design interactions can be defined as critical characteristics in terms of spatial, energy, information and materials[18]. In the concurrent model of systems engineering, as the design progresses and aircraft system design becomes temporarily fixed, more information can be extracted from the product model. Since 3D CAD is the main engineering data that connects design and manufacturing, the proposed method in this research should consider the improvement of information involved in it. The developing method should help both product designers and FAL designers to understand system functions and interactions based on integrated CAD.

3.1. FAL design phases towards product design

SAE guideline ARP4754A[3] and other aircraft development references state the development process in systems engineering life-cycle models. Most of these models are serial in manner, from product concept to manufacturing and retirement[15]. But this does not consider the relationship between product design and FAL design. For this research, the FAL design is parallel with product design, and both of them can be sub-divided into concept, definition and development phases. The detailed activities of each phase are then defined towards systems integration process.

The concept phase comprises the early FAL concepts and possible alternatives towards aircraft overall functions and specifications. In this phase, FAL design should decide the assembly layout based on process capacities, general station function and the balancing of design and manufacturing constraints. For a continuous moving assembly line, critical stations should be defined in the whole FAL process.

In the definition phase, FAL design obtains more detailed design information, such as system schematics, preliminary product 3D layout and systems interactions information to decide the FAL integration sequencing, FAL tasks allocation for each station, general resources configurations and technologies to be used. The design output also includes the detailed interfaces of installation and test in stations. The design results of this phase can be used as the input of FAL balancing in later phase. Refine actions can be taken if the results fail to meet the requirements set in concept phase.

The FAL design activities in the last phase development are more related to operations towards real production. This includes the 3D assembly simulation, detailed work instruction design, factory logistics design and FAL discrete event simulation. In this phase, more design constraints from real plant environment and operations are considered in FAL processes and documented in work instructions. These constraints include operation accessibility, foreign object damage (FOD) and safety factors. At this point, the FAL design is as prepared for real production. The later process in development is the system installation and test process from item to the final roll-out aircraft.

It can be concluded from the activities of FAL design phases that the FAL design decomposes product design information from aircraft to systems, sub-systems and items. By contrast, in later production the FAL plans compose the aircraft in a reversed way. Installations and tests are oriented their counterparts in FAL design. Then these activities can be listed in table 2. The critical characteristics abstracted from product interactions are allocated in the FAL design process and verified in the FAL production process. The tests in FAL production provide qualifications correspond to FAL design.

Table 2. FAL integration activities by aircraft system hierarchy

	Aircraft	Systems	Sub-systems	Items
FAL design	Line definition towards overall specifications	FAL tasks allocation	FAL tasks allocation	Operations and logistics design
FAL production	Final factory test and roll out aircraft	Integration of systems towards aircraft	Integration of sub-systems towards systems	Integration of items towards sub-systems

3.2. FAL integration model

The developing method aims to solve the complex system integration problem in FAL using more integrated engineering data that links design and manufacturing. This kind of data is defined as unified master data that contains traditional aircraft geometrical information and critical characteristics from system interactions. The data should also follow the single source of product data (SSPD) principle used in aerospace and cover the design and development life-cycle. The data can be refined only through the top-down development process. Thus, the data of engineering information sources should have the following characteristics:

- System interactions and critical information modelling
- Integration of 3D CAD and non-geometric feature data
- Model reusability in development life-cycle

System interactions are defined in early product design phase in terms of static and dynamic behaviours. Model based systems engineering (MBSE) tool Modelica/Dymola can be used to design and analyse the system behaviours. Other critical information includes the failure mode and effects analysis (FMEA) data, operations and safety requirements from FAL. Typical software selection for FMEA design is PTC Windchill Quality Solutions. Since most of the information is non-geometric feature data, the developing data should associate system non-geometric feature data with related 3D geometries. Currently, Dassault Systèmes CATIA V6 is the leading 3D CAD system used in both aircraft design and manufacturing. This system also embeds Dymola environment to support systems behaviour modelling[19]. Thus, system interactions data defined in product design can be transmitted to FAL design. In the development process, data can be inherited from each product design phase to FAL design. Thus, based on the definitions of FAL design and activities in table 2, the FAL integration model can be then shown in systems engineering V model in concurrent engineering (as shown in Figure 4).

The FAL integration V model covers the life-cycle duration from concept to the end of final assembly. The two sides of the V model represent the FAL design and real integration process from an analytical and physical view respectively. The industrial software packages and critical characteristics are mapped onto the FAL design process in the model. The left top-down process works from the specifications of overall aircraft, through the FAL task allocation of systems and sub-systems to the detailed operations and logistics design. On the right bottom-up process, tests alternate with installations providing the qualification of left side counterparts by layers.

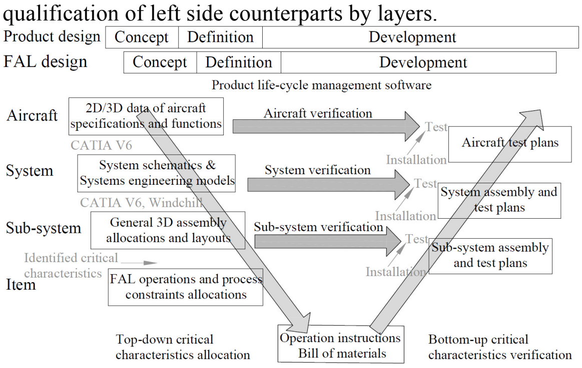

Fig. 4. FAL integration V model (Life-cycle model based on SAE APR4754A and Mas [3,5])

The proposed method focuses on early FAL design phases, especially the FAL tasks allocation work in definition phase. The implementation architecture mapping with industrial packages and data exchanges are then illustrated in figure 5.

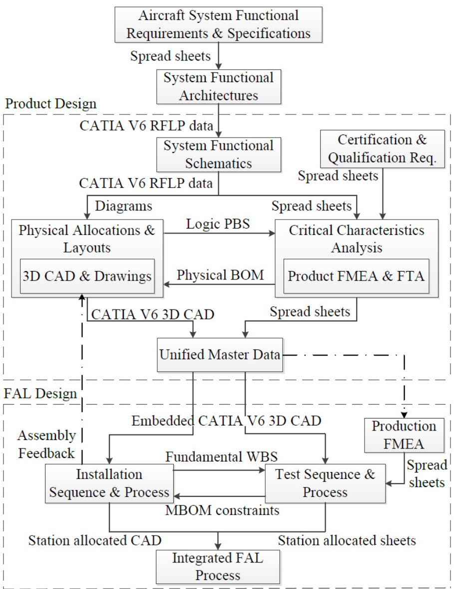

Fig. 5. Implementation architecture for FAL design

The data exchange between product design and FAL design can be seen from the implementation architecture. The systems interactions and schematics are defined in CATIA V6 RFLP (Requirements, Functional, Logical, Physical) module[19]. Then this information is allocated to general physical layout, and then further associated with qualification requirements. The two aspects of information which stand for mechanical installation and functional test respectively, form the unified master data for FAL design.

3.3. Initial case study

The concept study is based on a Cranfield University student group design project aircraft. Figure 6 shows the simplified schematic of four systems and the CATIA 3D master geometry model from system physical allocations in early system design.

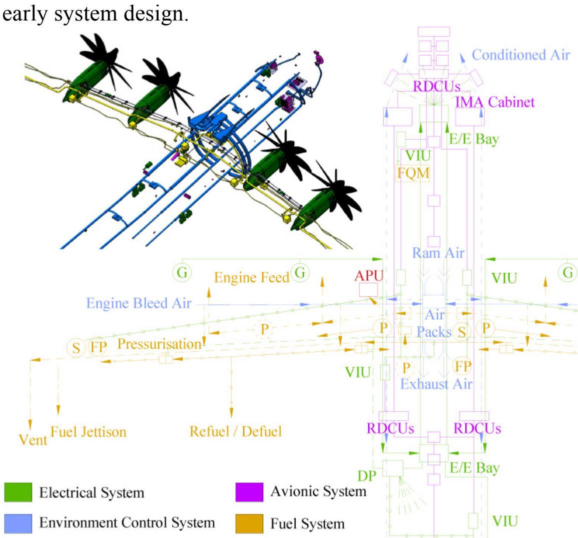

Fig. 6. Simplified systems schematic and 3D master geometry model[20]

Several different types of interaction are defined in the systems schematic including:

- Fuel flow: fuel transfer, engine feed, refuel/defuel, jettison
- Air flow: engine bleed, cabin air distribution, avionics cooling, fuel tank pressurization and vent
- Electrical energy: power supply and remote distribution for other systems
- Information flow: sensor/probe data, system control logic transform through remote data concentrator unit (RDCU) and vehicle interface unit (VIU) to the central computer

The interactions can be classified in four aspects shown in Table 3.

Table 3. Degrees of system interactions in four aspects

	Electrical	Avionic	ECS	Fuel
Spatial	Strong	Medium	Strong	Strong
Energy	Strong	N/A	N/A	Strong
Information	Medium	Strong	Weak	Weak
Materials	Medium	Weak	Strong	Strong

The work of FAL task allocation then begins with CATIA 3D models which represent the spatial interactions for system components installation process design. Systems installation tasks are arranged in sequences for FAL stations based on DFMA analysis towards system hierarchy. For example, the engine bleed air is the source for air distribution, avionics cooling and fuel tank pressurization. These system interfaces are pipe connectors and valves shown in 3D models. Thus the decision of general installation priorities can be made as: install the components of air source and end sides first, and then finish the connection and joining of interfaces. However, since these sub-systems should satisfy the designed function after installation, mechanical tests, or in this example airtightness tests are used to check the leakage of finished installations. In fact, it is difficult to understand the air flow interactions from 3D models and design the sequencing of airtightness tests for sub-systems and overall system.

More interactions are found in electrical energy and information flow with integrated modular avionics (IMA) or other similar integrated architectures. The finished electrical installations would provide electrical energy to the central computer and system equipment, while the control logic of electrical system and other systems are embedded in the central computer. In the FAL stations, tasks require physical installations from 3D geometrical information and energy flow, control logics from schematics to fulfil and verify the designed functions. Many of those interactions are also dynamic system behaviours. In the current system design process, the 3D CAD and systems schematics are not well integrated at the early design stage, but they are both required for generating a feasible FAL overall process.

4. Benefits and Challenges

The developing method could offer some advantages in terms of better integration of design data source, fulfilling of system functions verification and bringing FAL design earlier involved into product design process, which supports the decision making of manufacturing strategies at early design stage and reduce potential risks caused by poor FAL plans. However, it could be argued that this method also faces challenges including the lack of design information at the right time for FAL early design, the complexity of system behaviour modelling towards FAL design constraints and the design process concurrence and management.

5. Conclusion

The interrelationship between aircraft systems and FAL design is discussed and concluded in this paper that the nature of aircraft final assembly is complex system integration at the manufacturing stage. The FAL design method is therefore developed based on systems engineering principles. An integrated 3D CAD implementation architecture is proposed towards system interactions and critical characteristics aiming to better integration of installation and test in FAL especially at early design stage. The next step work is to define the CATIA V6 systems engineering models with 3D geometry and system behaviours that would constrain the FAL design and test the developed model using a representative design.

Acknowledgements

The case study in this research is based on the Cranfield University multipurpose air freighter F-14 Hermes.

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2017-05-09

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Elsevier

Tao Li, Helen Lockett, An investigation into the interrelationship between aircraft systems and final assembly process design, Procedia CIRP, Volume 60, 2017, Pages 62-67

http://dx.doi.org/10.1016/j.procir.2017.01.056